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“Farming with alternative pollinators” provides benefits also in large-scale fields

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ABSTRACT

Insect pollinators are declining worldwide due to many challenges and several approaches have been implemented to mitigate their loss. Farming with Alternative Pollinators (FAP) uses marketable habitat enhancement plants (MHEP) that yield substantial benefits for farmers from the first year. Studies with small-scale farmers have shown that FAP sustains high diversity and abundance of flower visitors and natural enemies, resulting in significant increases in smallholders' incomes, on average 121% higher. For the first time, we analyzed this approach in large-scale fields. Trials were conducted in 16 farms in two regions of Morocco, Sidi Slimane and Ksar El-Kebir, in 2021. We used melon (Cucumis melo) as the main crop and coriander, anise and sunflower as MHEP and selected in each farm 1 ha as trial area in larger monocultures. We compared FAP and control fields regarding abundance and richness of flower visitors, natural enemies and pests as well as net income of the whole field (1 ha). Flower visitors and natural enemies were significantly more diverse and abundant in FAP fields and there were also fewer pests. Our economic results show 17% higher net income per ha in FAP fields versus control fields in the Ksar El-Kebir region, and 12% higher net income in FAP fields compared to control fields in Sidi Slimane region. Although the mean yield difference was statistically significant, the income difference was not. We suggest more FAP trials are needed in different large-scale fields systems.

1. Introduction

Melon (Cucumis melo) is a crop of high importance worldwide due to its capacity to adapt to different kinds of soil and climates (Bisognin, 2002). It is grown in temperate as well as tropical regions (Bisognin, 2002; Klein et al., 2007). Melon has a high marketable value and is considered an important crop that depends on pollinators (Klein et al., 2007; Rodrigo Gómez et al., 2016). Animal pollinators are categorized “essential” for melon (Klein et al., 2007; Rodrigo Gómez et al., 2016). At peak harvest, melon is affordable for lower-income populations, making it an important staple crop (Singh et al., 2022). Melons are nutritionally valuable, providing carotenoids, vitamins A, C, B6 and B1, iron, calcium, magnesium and potassium (Fleshman et al., 2011; Vincente et al., 2014). The crop is economically valuable worldwide, yielding a very high income within a short timeframe (Singh et al., 2022). Global melon production in 2020 was 28 million tons (FAO, 2020). The crop is particularly important in Mediterranean and Central Asian countries. North Africa produces 66,000 tons per year (Bisognin, 2002). In Morocco, melon production is rapidly increasing due to the European export market, with over 16,000 ha and 50,000 tons in 2020 (FAO, 2020). Many farmers use honeybee hives in their fields to improve crop pollination (Breeze et al., 2019), but sweat bees are the most efficient pollinators of melon (Campbell et al., 2019). A recent study confirmed that the wild bee species Lasioglossum malachurum (ground-nesting bee) is a key floral visitor and an abundant pollinator of melon in Morocco (Bencharki et al., 2022; El-Abdouni et al., 2022).

However, wild pollinators are declining worldwide (Zattara and Aizen, 2021). Climate change effects are causing additional risks for pollinators (Pudasaini et al., 2015), potentially threatening melon and other pollinator-dependent production worldwide. Intensive pesticide

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use also threatens wild and domesticated bees and associated melon production (Tsvetkov et al., 2017).

Natural enemies are important for controlling insect pests in crops, reducing crop damage and the need for pesticides. Protecting natural enemy populations can have a positive impact on crop yields (Clough et al., 2011; Gurr et al., 2016, 2017; Martin et al., 2013; Östman, 2004; Östman et al., 2003). Pest control can also be affected by the composition of the landscape (Bianchi et al., 2006). A diversified landscape can enhance biodiversity and contribute to the conservation of natural enemies (Bianchi et al., 2006; Holland et al., 2017; Tscharntke et al., 2012).

Ecological intensification represents a critical strategy for mitigating the effects of climate change and promoting sustainable development worldwide in order to sustain biodiversity, ecosystem services and human well-being (Kleijn et al., 2019; Kremen, 2020). Farming with Alternative Pollinators (FAP) was developed as a scalable alternative to (paid) wildflower strips (WFS), which are not affordable for low- and middle-income countries (Christmann, 2020; Christmann et al., 2017, 2021a, 2021b; Christmann and Aw-Hassan, 2012). FAP uses marketable habitat enhancement plants (MHEP, e.g., oil seeds, spices, food crops and medicinal plants) within fields to provide diverse floral traits, such as shape, color and flower type as well as nesting support from local or waste materials. The effects of habitat enhancement are measured by comparing the diversity and abundance of flower visitors, natural enemies, pests and net income. Net income is the method-inherent and performance-related incentive replacing payments through agro-ecological schemes (Christmann and Aw-Hassan, 2012; Christmann et al., 2017, 2021a, 2021b). MHEP attract a high diversity and abundance of flower visitors as well as natural enemies (Bencharki et al., 2022; Christmann et al., 2017, 2021a, 2021b). Field trials with smallholders were started in Uzbekistan on cucumber (2013–2014) and since 2015 (Christmann et al., 2017), their use has expanded in Morocco (Christmann et al., 2021b). FAP works the same way in all countries (e.g. central Asia or Africa), only the selection of MHEP and cultivars varies. Trials with zucchini, other cucurbits, have been conducted in Morocco (2018–2019), in Turkey, Algeria, Jordan and Palestine in 2020–2022. FAP has been tested also with other crops like okra and tomato in different continents. Since 2021, they have also been introduced into large-scale fields. FAP includes a policy component, which however is not relevant for this research.

Previous work (Bencharki et al., 2022; Christmann et al., 2017, 2021a, 2021b; El-Abdouni et al., 2022; Sentil et al., 2022a) demonstrated the positive impact of FAP in small fields (300 m^2) by increasing floral visitor diversity and abundance. Natural enemy abundance, by reducing pest populations, supports higher net incomes.

The current study assesses FAP efficiency in supporting pollinators and natural enemies in large melon fields (1 ha) in Morocco, with four objectives.

1) Compare the diversity and abundance of flower visitor communities in large fields between two different treatments (FAP vs. control) and across two areas (Ksar El-Kebir and Sidi Slimane).
2) Compare the diversity and abundance of melon flower visitors in strips of melon close to edges, referred to as "border", and at center of FAP fields.
3) Compare the abundance of pests and natural enemies in two different treatments (FAP vs. control).
4) Compare the average net income (in Moroccan Dirham, MAD) between FAP and control fields in each region.

Our general hypothesis posits that implementation of the FAP approach will lead to an increase in flower visitors and natural enemies as well as net income in large fields, but much lower than in trials in smallholder fields.

2. Materials & methods

2.1. Study sites

Fieldwork was performed in two different areas of Morocco (Sidi Slimane and Ksar El-Kebir). Sidi Slimane is located in the northwestern Gharb region of Morocco (34°02′N 6°50′W, 54 m. a.s.l.) between Kenitra and Meknes. The study area is located in the southeastern sector of the Gharb plain, in the transition zone between the Maâmora forest and the Meknes mountains, bound to the north by Sidi Kacem province (known for high altitude olive orchards and mountains), to the south by the rural commune of Boumaiz (province of Sidi Slimane, known for citrus production) and to the west by the rural communes of Kecybia and Sfafaa (provinces of Sidi Slimane, known for large-scale citrus and vegetable production).

Ksar El-Kebir is situated in the northwestern Chamal region of Morocco (34°59′56″N 5°54′10″W, 3 m. a.s.l.), about 160 km north of Rabat, 32 km from Larache and 110 km from Tangier. The study area in Ksar El-Kebir is by the Loukkos river, bound to the west by the edge of the Gharb region (known for fruit and vegetable production), to the east and south by the Ouezzane region mountains and to the north by the Rifan mountain range (which provides almost 20% of Morocco's sugar needs and also produces melon in large fields).

Both areas have continental Mediterranean climate (subtype temperate with cold winters, hot and dry summers, with an annual rainfall of 400–450 mm per year). The two study areas differ in altitude: the highest altitude in the Ksar El-Kebir region is 6 m, while altitudes in Sidi Slimane region can reach up to 68 m. In both areas, melon is an important crop and during the sampling period, approximately 90% of the crops were harvested at the same time.

Comparisons are based on a 1-year study (2021). Melon has an annual production cycle. The main crop and MHEP were seeded at different times depending on the region, i.e. late March in the Sidi Slimane region and late May in the Ksar El-Kebir region. The management of melon at the study sites was consistent and the farmers refrained from using any pesticides throughout the study period. This decision was based on the potential negative impacts of pesticides on biodiversity, including pollinator populations and other beneficial insects.

To avoid bias, the farmers seeded one local variety in both regions. All farmers used drip irrigation. FAP fields were replicated five times, planted 1–5 km apart, and control fields were replicated three times in each region, sometimes less than 1 km apart. The studied plot areas were 1 ha (100 × 100 m), and MHEP strips were 1 m wide x 100 m long, spaced 15.5 m apart in each FAP field (Fig. 1). In control fields, only the main crop (100% monoculture) was established (Fig. 1). There were no honeybee hives around melon fields. We selected fields surrounded by pollinator-independent crops, such as maize, wheat or potato.

In each FAP field, we used three MHEP, seeded separately. These were coriander (Coriandrum sativum), sunflower (Helianthus annuus) and anise (Pimpinella anisum). MHEP plants were chosen in consultation with farmers based on their attractiveness, flowering and potential income.

2.2. Flower visitor sampling

2.2.1. Pollinator sampling

We surveyed the wild pollinator communities using hand netting and pan trapping, following a standardized protocol (Westphal et al., 2008). Each field was sampled three times during the blooming season of the main crop, starting from May to June in Sidi Slimane and July to August in Ksar El-Kebir (Table 1). All insects were collected, except honeybees (*A. mellifera*) and Xylocopa pubescens, as they were identifiable in the field.

Sweep net sampling rounds were conducted for two days from 10:00 to 16:00 in 100 × 15.5 m^2 plots, two per area. Each field was sampled once for 25 min during each sampling round, only under favorable

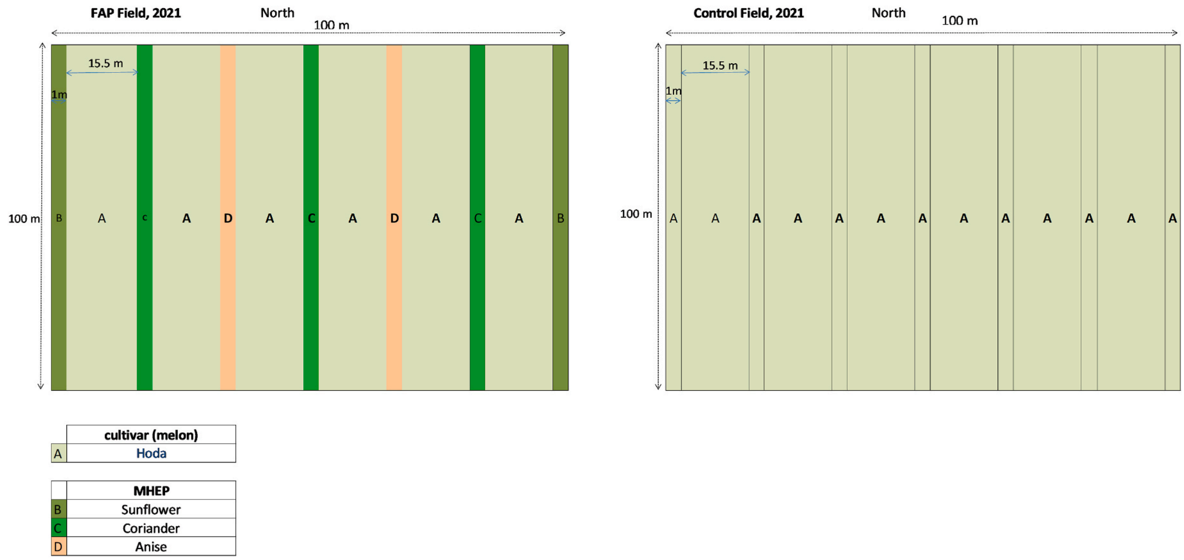

Fig. 1. Experimental design of melon for Sidi Slimane and Ksar El-Kebir.

weather conditions (i.e. temperature above 16 °C, clear skies and calm wind). In the main crop in both treatments (FAP and control), we collected flower visitors of melon for 10 min along two transects (5 min per transect). Transect 1 (T1) was the main crop edge and transect 2 (T2) was in the center of the field to compare edge and center of FAP fields (Fig. 2 Supplementary Material). In the FAP fields, we walked transect 3 (T3) along the MHEP for 15 min (5 min in sunflower, 5 min in coriander and 5 min in anise). In the control fields, we sampled for 15 min accordingly (same area of 100 × 1 m^2) (Fig. 1 Supplementary Material). The collected bees were killed in a jar with ethyl acetate. Pan traps were used to collect the complete entomofauna in FAP and control fields. We used yellow, white and blue UV-reflective paints (Rocol Top, Belgium) on 500 ml (145 mm diameter, with 45 mm depth) pan traps filled halfway with odorless soapy water. We placed 12 sets of three pan traps on the ground in four locations, two in the center of the field and the other two at the edge of the field, for 30 h. All wild bee specimens collected were curated in the lab (i.e. pinned, labelled and digitized). The genus level of wild bees was determined for each specimen by using the Michez et al. (2019) key. Next, the sorted material was sent to taxonomists for identification to species level (Lhomme et al., 2020). Bees were identified by different taxonomists to species level (see Acknowledgements). Remaining non-bee insects were identified to family or genus level.

2.2.2. *Sampling of pests and natural enemies*

We sampled pests and natural enemies in the main crop and MHEP in FAP fields. Sampling was carried out three times in each field simultaneously with pollinators sampling. Plant beating was used to collect pests and natural enemies in addition to transects. For FAP fields in both types of crops, main crop and MHEP, we selected ten plants of the main crop randomly from the whole field and ten plants from each MHEP from the edges and the center of the field. In control fields, we sampled only in the main crop where we selected ten plants of the main crop randomly from the whole field. To standardize the method, the plants were struck ten times by a stick fitted at its end with a rubber cover. The insects fell into the trap and were collected in a plastic bag. Next, samples were pooled in 2 ml Eppendorf tubes containing 70% ethanol after sorting of the samples by use of binoculars (Bonsignore and Vacante, 2012).

2.3. *Economic assessments*

FAP and control fields encompassed 1 ha. In FAP fields, 93% of the area was used for the main crop (melon), while 7% of the area was used for MHEP. For the control fields, the whole 1 ha was planted with the main crop, i.e. melon (Fig. 1). The 7% area corresponding to the MHEP areas in FAP fields was marked and harvested separately to ensure appropriate comparison of melon production in FAP and control fields. Both the main crop and MHEP were harvested by hand.

The average net income was calculated based on the number and the weight of melon fruits and – in FAP fields, the yield of MHEP. We counted the number and weight of melon fruits in ten randomly selected 1 × 1 m^2 quadrants. Based on these results, we calculated the number and weight of the melon fruits across each field. The income from the 93% zone of the main crop was calculated by multiplying total weight by the market price per kg in 2021. Due to practical constraints, we did not evaluate quality of the yield (i.e. individual size and shape of melon fruit), storability or annual variation of prices.

For MHEP (7% zones) in FAP fields and the equivalent area (7% zones) in control fields, FAP farmers weighed and recorded the yield (seeds) of each MHEP and control farmers weighed and recorded the total weight of melon. Income was calculated by multiplying total weight by the market price per kg in 2021. We deducted respective investment costs for seeds and extra-work required for MHEP cultivation in the 7% zones of FAP fields, estimated to be 200 MAD (three persons per day per field) as labor costs for MHEP harvesting. We did not take into consideration labor costs for harvesting the 7% zones in control fields as they can easily be harvested together with the main crop (**Tables 2 and 3**). We calculated the MHEP income of farmers per hectare for FAP fields in comparison to monoculture fields.

2.4. *Statistical analysis*

All statistical tests were conducted in R software (version 4.4.0; R Development Core Team, 2023).

We used a two-way ANOVA analysis to evaluate whether there was a significant interaction between two independent variables in combination. We tested "Treatments" and "Regions", "MHEP strip location within FAP fields" and "Regions" and their effects on mean abundance and species richness of flower visitor communities.

First, the model incorporated two treatments (FAP and control) and

Table 1
Seeding and blooming times of the main crop and of marketable habitat enhancement plants during the melon trials in 2021 for both regions (Sidi Slimane and Ksar El-Kebir).

	Seeding time				Blooming time																										
2021	March				April						May								June						July					August	
	1	2	3	4	1	2	3		4		1	2	3					4	1		2		3	4	1	2		3	4	1	2
Sidi Slimane experimental trial																															
Sampling timing																															
Cucumis melo					1	3	3	3	3	3	3	3	3	3				3		3		3	3	2							
Coriandrum sativum								1	2		3	3		3				3		3		3	3	2							
Helianthus annuus												2		3	3			3		3		3	3	3	3		2				
Pimpinella anisum									1		3	3		3				3		3		3	3	3	3		3	3	3	2	1
	Seeding time								Blooming time																						
2021	May				June						July								August						September					October	
	1	2	3	4	1	2	3		4		1	2	3			4	4		1		2		3	4	1	2		3	4	1	2
Ksar El-Kebir experimental trial																															
Sampling timing																															
Cucumis melo									3		3	3		3				3		3											
Coriandrum sativum								1	3		3	3		3				3		1											
Helianthus annuus								1	2		3	3		3				3		3		3	3	3	1						
Pimpinella anisum												2	2	3				3		3		3	3	3	3	1	1				

Flower coverage scale
1 10–25%
2 25–50%
3 50–100%

two regions (Ksar El-Kebir and Sidi Slimane) as the primary explanatory variables, with regions included as a random effect. We then analyzed abundance and species richness of flower visitor in different treatments across regions. In the second analysis, we used location of MHEP strips in FAP fields (edge and center) and regions (Ksar El-Kebir and Sidi Slimane) as variables, with regions always as a random effect.

To check for normality, QQ plot and Shapiro-Wilk tests of normality were used. Homogeneity of variances was assessed by Levene's test from the car package (version 3.1–2) (Fox and Weisberg, 2019). To illustrate this analysis, we created a boxplot graph. These graphs include the p-values obtained from pairwise multiple comparisons, calculated using the Estimated Marginal Means (emmeans) test function from the rstatix package (version 0.7.2) (Kassambara, 2019). For pairwise comparisons, we used a Bonferroni adjustment.

For the following analyses, we focused on natural enemies and pests. Data collected from each field separately (FAP and control) and all sampling dates mixed from different regions (Sidi Slimane and Ksar El-Kebir) were pooled to generate a species accumulation curve using the vegan package (Oksanen et al., 2022). A heatmap was constructed using the heatmap package (Galili et al., 2018) to visualize interaction between natural enemies/pests and fields using the relative abundance of each specimen visiting each field.

To test the hypothesis that yield and income in FAP fields were not significantly different from those of the control fields, we used a *t*-test for independent samples to compare yield (weight per kg) and income per MAD (Moroccan Dirham) differences between FAP and control fields. In this analysis, we used a two-tailed result as it can be more precisely defined rejection region locations (Pallant, 2016).

3. Results

During sampling of flower visitors, we collected and observed a total of 5124 specimens, including 2917 specimens of *Apis mellifera* (56.9%) (Table 4). In the Ksar El-Kebir region, we collected 1622 wild specimens: 76.2% were wild bees belonging to nine different genera (Andrena, Ceratina, Coelioxys, Colletes, Halictus, Hylaeus, Lasioglossum, Megachile, Nomada, Nomiapis, Osmia, Sphecodes and Xylocopa), 21.3% were wasps (Leucopsis, Polistes and Vespidae) and 2.5% were hoverflies, Syrphidae (Eristalinus, Eristalis, Eupoedes, Ischiodon, Paragus, Sphaerophoria and Syritta). In Sidi Slimane, we collected 585 specimens of wild species, including 29.4% Syrphidae (Sphaerophoria and Syritta), 62.1% wild bees from eight different genera (Andrena, Ceratina, Colletes, Halictus, Hylaeus, Lasioglossum, Nomiapis and Osmia) and 8.5% wasps (Polistes and Vespidae).

In Ksar El-Kebir, we collected 242 specimens of pests and 175 specimens of natural enemies. Pests included 51.2% Thysanoptera: Thripidae, 28.5% Hemiptera: Aphididae, 6.2% Coleoptera: Meloidae, 2.1% Coleoptera: Chrysomelidae and 5.4% of other Coleoptera we were unable to identify to family, 1.6% Lepidoptera, Noctuidae, 1.6% Hemiptera: Cicadellidae, 0.8% Hemiptera: Pentatomidae, 0.8% Coleoptera: Curculionidae, 0.4% Lepidoptera, Noctuidae, 0.4% Hemiptera: Psyllidea and 0.8% other Hemiptera.

Regarding natural enemies we found 62.8% wasps (Hymenoptera), 10.9% Thysanoptera: Aeolothripidae, 8% Hemiptera: Anthocoridae, 7.4% Hemiptera: Miridae, 5.7% Neuroptera: Chrysopidae, 3.4% Coleoptera: Coccinellidae, 1.1% Phlaeothripidae: Phlaeothripinae and 0.6% Thysanoptera: Thripidae. In Sidi Slimane, we collected 163 specimens of pests and 243 specimens of natural enemies. Pests included 35.6% Hemiptera: Aphididae and 2.4% other Hemiptera which we were unable to identify to family, 18.4% Thysanoptera, Thripidae, 15.3% Hemiptera: Psyllidea, 11.6% Hemiptera: Cicadellidae, 9.2% Coleoptera: Meloidae, 4.3% Coleoptera: Chrysomelidae, 2.4% other Coleoptera and 0.6% Hemiptera: Pentatomidae.

Natural enemies included 23.9% wasps (Hymenoptera), 17.3% Hemiptera: Anthocoridae, 12% Thysanoptera: Aeolothripidae, 14.8% spiders (Araneae), 11.1% Neuroptera: Chrysopidae, 10.7% Coleoptera:

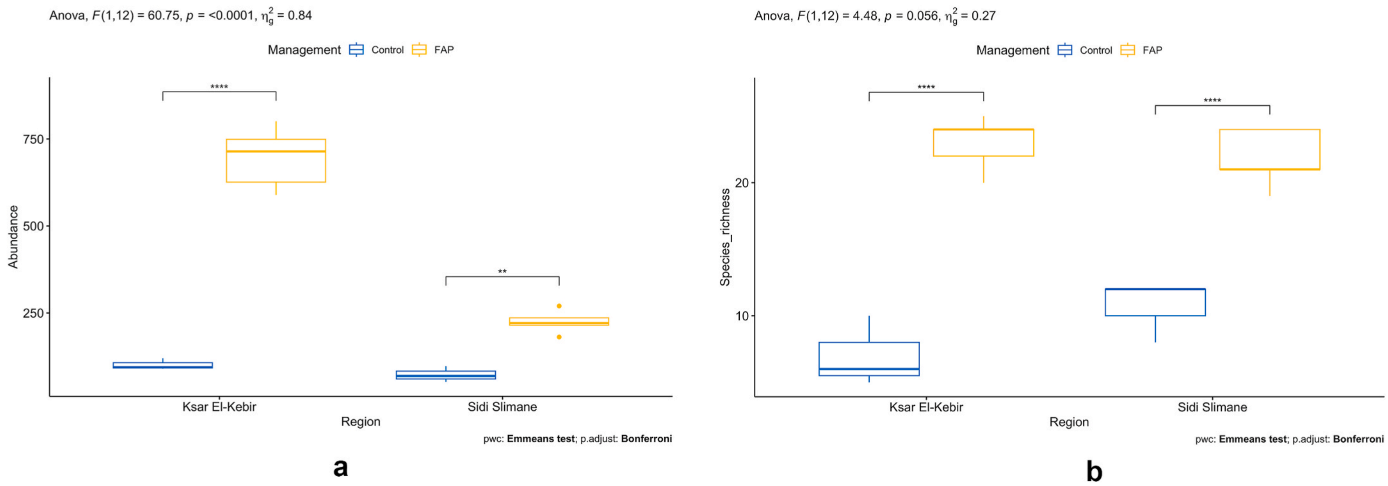

Fig. 2. Boxplots encompassing the difference of mean abundance (Fig. 2a) and species richness (Fig. 2b) of flower visitors between the two types of sites of FAP fields (93% zone main crop and 7% zone MHEP) and control fields (100% zone main crop) in the two regions, Ksar El-Kebir and Sidi Slimane. Significant differences are shown by the statistical test (emmeans).

Table 2
Economic assessment calculation of melon in Ksar El-Kebir.

Treatment	Number of harvested melon 93%-zone	Total weight of harvested melon in kg/93% zone	Price MAD/kg	Income from 93% zone in MAD	Gross income from 7% zone in MAD	Investment in 7% zone in MAD	Additional labor cost for the habitat zone in MAD	Total net income from 7% zone	Total net income from 1 ha in MAD
FAP 1	49,290	88126.8	2	176,254	3844	83	200	3561	179,815
FAP 2	48,360	87001.5	2	174,003	4019	83	200	3736	177,739
FAP 3	49,290	88,164	2	176,328	3988	83	200	3705	180,033
FAP 4	42,780	78994.2	2	157,988	3892	83	200	3609	161,597
FAP 5	48,360	88563.9	2	177,128	4366	83	200	4083	181,210
control 1	40,920	74,772	2	149,544	9100	375	0	8725	158,269
control 2	35,340	65,379	2	130,758	8540	375	0	8165	138,923
control 3	39,060	73163.1	2	146,326	8260	375	0	7885	154,211
	Average number of harvested melon 93%-zone	**Average weight of harvested melon in kg/ 93% zone**	**Average income from 93% zone in MAD**	**Average total net income from 7% zone**	**Average net income from 1 ha in MAD**				
FAP	47,616	86,170	172,340	3739	176,079				
Control	38,440	71,105	142,209	8258	150,468				
% change	24	21	21	−55	17				

Table 3
Economic assessment calculation of melon in Sidi Slimane.

Treatment	Number of harvested melon 93%-zone	Total weight of harvested melon in kg/93% zone	Price MAD/kg	Income from 93% zone in MAD	Gross income from 7% zone in MAD	Investment in 7% zone in MAD	Calculated additional labor cost for the habitat zone in MAD	Calculated total net income from 7% zone	Total net income from 1 ha in MAD
FAP 1	29,760	51,401	2	102,802	3289	83	200	3006	105,808
FAP 2	63,240	105,081	2	210,161	3925	83	200	3642	213,803
FAP 3	49,290	82,714	2	165,428	3524	83	200	3241	168,669
FAP 4	55,800	95,306	2	190,613	4183	83	200	3900	194,513
FAP 5	52,080	90,498	2	180,997	3790	83	200	3507	184,504
control 1	35,340	66,132	2	132,265	7840	375	0	7465	139,730
control 2	50,220	83,895	2	167,791	9240	375	0	8865	176,656
control 3	41,850	69,927	2	139,853	8568	375	0	8193	148,047
	Average number of harvested melon 93%-zone	**Average weight of harvested melon in kg/ 93% zone**	**Average income from 93% zone in MAD**	**Average total net income from 7% zone**	**Average net income from 1 ha in MAD**				
FAP	50,034	85,000	170,000	3459	173,459				
Control	42,470	73,318	146,636	8174	154,811				
% change	18	16	16	−58	12				

Table 4
Abundance of flower visitors of melon and MHEP over one year in two different regions (Ksar El-Kebir and Sidi Slimane).

Region	Group	Bee/wasp family; fly genus	Species	Abundance
Ksar El-Kebir	Bee	Andrenidae	Andrena miegiella	1
		Apidae	*Apis mellifera*	2161
			Nomada maculatus	2
			Xylocopa pubescens	2
			Ceratina albosticta	1
			Ceratina chalybea	1
		Colletidae	Hylaeus annularis	390
			Hylaeus soror	194
			Hylaeus absolutus	54
			Hylaeus cornutus	53
			Colletes nigricans	1
			Hylaeus imparilis	1
		Halictidae	Seladonia gemmea	372
			Nomiapis bispinosa	99
			Halictus scabiosae	14
			Sphecodes puncticeps	9
			Sphecodes gibbus	8
			Lasioglossum discum	3
			Lasioglossum malachurum	2
			Lasioglossum minutissimum	2
			Lasioglossum villosulum	2
			Halictus fulvipes	1
			Lasioglossum leucozonium	1
		Megachilidae	Megachile fertoni	9
			Megachile apicalis	6
			Osmia notata	5
			Coelioxys argentea	3
	Syrphidae	Eristalinus	Eristalinus megacephalus	15
			Eristalinus taeniops	2
		Eristalis	Eristalis arbustorum	1
		Eupeodes	Eupeodes corollae	1
		Ishiodon	Ischiodon aegyptius	1
		Paragus	Paragus quadrifasciatus	4
		Sphaerophoria	Sphaerophoria scripta	3
			Sphaerophoria rueppellii	1
		Syritta	Syritta pipiens	10
			Syritta flaviventris	2
	Wasp	Leucospidae	Leucospis intermedia	7
		Vespidae	Polistes gallicus	125
			Polistes dominula	54
			Polistes austroccidentalis	1
			Vespidae Eumeninae	159
Sidi Slimane	Bee	Andrenidae	Andrena flavipes	137
			Panurgus calceatus	44
			Andrena fulvicornis	26
			Andrena numida	3
			Andrena langadensis	2
			Andrena verticalis	2
			Andrena miegiella	1
			Andrena ventralis	1
		Apidae	*Apis mellifera*	756
			Bombus terrestris	8
			Eucera eucnemidea	5
			Nomada bifasciata	3
			Ancyla brevis	1
			Ceratina albosticta	1
			Nomada glaucopis	1
		Colletidae	Hylaeus cornutus	7
			Colletes nigricans	1
			Hylaeus signatus	1
			Hylaeus soror	1
		Halictidae	Seladonia gemmea	42
			Lasioglossum villosulum	21
			Nomiapis bispinosa	13
			Lasioglossum malachurum	7
			Lasioglossum minutissimum	7
			Lasioglossum subhirtum	6
			Lasioglossum pauperatum	5
			Lasioglossum interruptum	4
			Halictus fulvipes	3
			Halictus flavipes	2
			Lasioglossum leucozonium	2
			Halictus scabiosae	1
			Seladonia smaragdula	1

(*continued on next page*)

Table 4 (*continued*)

Region	Group	Bee/wasp family; fly genus	Species	Abundance
			Lasioglossum nitidiusculum	1
		Megachilidae	Osmia notata	2
			Osmia versicolor	1
	Syrphidae	Eristalis	Eristalis tenax	3
		Eumerus	Eumerus amoenus	1
			Sphaerophoria scripta	121
		Sphaerophoria	Sphaerophoria rueppellii	35
		Syritta	Syritta pipiens	12
	Wasp	Vespidae	Polistes dominula	36
			Polistes gallicus	8
			Vespidae Eumeninae	5
			Vespula germanica	1
			total	5124

Coccinellidae, 7.8% Hemiptera: Miridae, 2% Phlaeothripidae: Phlaeothripinae and 0.4% Thysanoptera: Thripidae (Table 5).

3.1. FAP effects on diversity and abundance of flower visitors in entire fields

MHEP extended the flowering period up to 80.5 days in FAP fields, while the control fields sustained only 46 days of flowering (**Table 1**). The results showed a significant difference of abundance and species richness of flower visitors over a prolonged flowering period between both regions, Ksar El-Kebir and Sidi Slimane ($p < 0.05$) (Fig. 2). There was a statistically significant difference between FAP fields and control fields as well as on the effect of the regional landscape on abundance of the flower visitors ($F (1, 12) = 60.75$, $p = 0.0001$, $Eta^2 = 0.84$). Flower visitors abundance was significantly higher in FAP fields compared to control fields for both regions: Ksar El-Kebir ($F (1, 12) = 219$, $p < 0.0001$) and Sidi Slimane ($F (1, 12) = 14.3$, $p < 0.003$) (Fig. 2). Bee species richness was significantly higher in both regions in FAP fields compared to control fields: Ksar El-Kebir ($F (1, 12) = 96.9$, $p < 0.0001$) and Sidi Slimane ($F (1, 12) = 46.9$, $p < 0.0001$) (Fig. 2). We found no statistically significant differences between FAP and control fields in either region for species richness of flower visitors, $F (1, 12) = 4.48$, $p = 0.056$, $Eta^2 = 0.27$.

3.2. Effect of MHEP position within field on flower visitors

No significant difference was observed between border and center of melon strips in FAP fields in terms of flower visitor abundance, nor was there any significant difference observed based on the region, $F (1, 16) = 0.39$, $p = 0.54$, $Eta^2 = 0.02$ (Fig. 3 Supplementary Material).

A comparison between border of FAP fields compared to center of FAP fields was performed without a statistical significance receiving a Bonferroni adjustment. There was no statistically significant difference in mean "Abundance" for both regions, Ksar El-Kebir ($F (1, 16) = 0.21$, $p > 0.2$) and Sidi Slimane ($F (1, 16) = 0.045$, $p > 0.8$), regarding insect availability between two locations (border vs. center) (Fig. 3 Supplementary Material).

There was no statistically significant difference between two locations of the FAP fields (border and center) and no effect of the region on species richness of the flower visitors, $F (1, 16) = 1.75$, $p = 0.2$, $Eta^2 = 0.1$.

There was no significant difference in mean species richness for both regions, Ksar El-Kebir ($F (1, 16) = 4.17$, $p > 0.05$) and Sidi Slimane ($F (1, 16) = 0.029$, $p > 0.8$), regarding flower visitor diversity between two locations (border vs. center) (Fig. 3 Supplementary Material).

3.3. FAP effects on pests and natural enemies

The heatmap program results illustrate the different abundances of natural enemies and pests in different sites of FAP and control fields in both Sidi Slimane and Ksar El-Kebir (Fig. 3). In Sidi Slimane, the most abundant pest in control fields was Aphis gossypii compared to FAP fields, where the most abundant pests were Psyllidae family. Among natural enemies, Orius sp and wasps were more abundant in FAP fields than in control fields. In Ksar El-Kebir, the most abundant natural enemies were wasps in some control fields. In control fields, some species of pests were abundant, such as Frankliniella occidentalis and Aphis gossypii, whereas in FAP fields, pests were rarely present.

3.4. FAP effects on net income

Economic assessment results demonstrate a difference between FAP and control fields in both regions (Ksar El-Kebir and Sid Slimane). In Ksar El-Kebir, the average net income from FAP fields was 17% higher than from control fields, whereas in Sidi Slimane, the average net income of FAP fields was 12% higher compared to control fields (Fig. 4). In the case of melon, the investment costs for MHEP (coriander, anise and sunflower) in the 7% area of the FAP fields were on average 76.1% lower than the investment in the 7% zone of control fields, due to the quite expensive melon seeds in Morocco.

The average weight per hectare from FAP fields was significantly higher than that from control fields (t Stat = 2.56, P two-tail = 0.02) (Supplementary Material, Table 1). However, the average net income (Supplementary Material, Table 2) was not significantly different between FAP and control fields (t Stat = 2.09, P two-tail = 0.055).

4. Discussion

4.1. FAP effects promoted by prolonged flowering time

We showed that FAP enhanced flower visitor diversity and abundance in large-scale fields (1 ha) in both regions. The FAP approach enhanced pollinator and natural enemies' populations in flower strips, whereby the beneficial insects shifted to the main crop, while control fields benefited only from the insects attracted by the melon flowers. Hence, in FAP fields, the yield was higher than in control fields (monoculture).

The mechanisms behind these positive effects are probably simple. The use of FAP fields has been shown to extend the flowering period to 80.5 days in fields seeded with MHEP compared to 46 days in control fields (Table 1). Diverse flowers are important for attracting and supporting a wide range of flower visitors (Christmann et al., 2021b). Further, some MHEP, such as coriander, host flower visitors important for melon, especially in spring (Azpiazu et al., 2020, Sentil et al., 2022a). Coriander hosts bees of the Lasioglossum genus, some of which are known melon pollinators (Bencharki et al., 2022; Pérez-Marcos et al., 2023). Results of this study on large-scale fields (1 ha) and parallel results from previous small scale trials (0.03 ha) have shown the value of FAP fields supporting diverse wildflower visitors (Bencharki et al., 2022; Christmann et al., 2017, 2021a, 2021b; El-Abdouni et al., 2022; Sentil

Table 5
Natural enemies and pests in Ksar El-Kebir and Sidi Slimane.

Ksar EL-Kebir				Sidi Slimane			
Pests		Natural enemies		Pests		Natural enemies	
Thysanoptera: Thripidae	51.20%	Wasps (Hymenoptera)	62.80%	Hemiptera: Aphididae	35.60%	Wasps (Hymenoptera)	23.90%
Hemiptera: Aphididae	28.50%	Thysanoptera: Aeolothripidae	10.90%	Other Hemiptera	2.40%	Hemiptera: Anthocoridae	17.30%
Coleoptera: Meloidae	6.20%	Hemiptera: Anthocoridae	8%	Thysanoptera, Thripidae	18.40%	Thysanoptera: Aeolothripidae	12%
Coleoptera: Chrysomelidae	2.10%	Hemiptera: Miridae	7.40%	Hemiptera: Psyllidea	15.30%	Spiders (Araneae)	14.80%
Other coleoptera	5.40%	Neuroptera: Chrysopidae	5.70%	Hemiptera: Cicadellidae	11.60%	Neuroptera: Chrysopidae	11.10%
Lepidoptera, Noctuidae	1.60%	Coleoptera: Coccinellidae	3.40%	Coleoptera: Meloidae	9.20%	Coleoptera: Coccinellidae	10.70%
Hemiptera: Cicadellidae	1.60%	Phlaeothripidae: Phlaeothripinae	1.10%	Coleoptera: Chrysomelidae	4.30%	Hemiptera: Miridae	7.80%
Hemiptera: Pentatomidae	0.80%	Thysanoptera: Thripidae	0.60%	Other Coleoptera	2.40%	Phlaeothripidae: Phlaeothripinae	2%
Coleoptera: Curculionidae	0.80%			Hemiptera: Pentatomidae	0.60%	Thysanoptera: Thripidae	0.40%
Lepidoptera, Noctuidae	0.40%						
Hemiptera: Psyllidea	0.40%						
Other Hemiptera	0.80%						

et al., 2021, 2022a,b).

Previous studies (Haaland et al., 2011; Marshall et al., 2006; Scheper et al., 2013) clearly demonstrated that abundance of bees was higher in fields with WFS compared to monocultures, but no difference was detected in the crop production (Albrecht et al., 2020; Campbell et al., 2017a,b; Quinn et al., 2017), including melon production (Azpiazu et al., 2020; Pérez-Marcos et al., 2023). Aizen et al. (2019) demonstrated that extensive monoculture is linked to limited pollinator availability and decreased pollination. Monocultures affect bee abundance and diversity (Hendrickx et al., 2007; Kennedy et al., 2013; Quintero et al., 2010), while agricultural diversification can enhance pollinator supply and pollination (Blaauw and Isaacs, 2014; Sardiñas and Kremen, 2015). Our study showed that strips of MHEP every 15 m enhance diversity and abundance of flower visitors and natural enemies as well as productivity. Therefore, we assume that also within monocultures, such strips seeded in short distance might not only be effective for insect conservation, but also enhance the productivity of pollinator-dependent crops in monocultures and thus support bending the curve described by Aizen et al. (2019).

4.2. *Effect of position of MHEP within field*

In this study, we analyzed the spillover of flower visitors from MHEP to the main crop in different parts of the field, including center and border. We found that there was no significant difference between border and center of the FAP fields in terms of flower visitor abundance and species richness. Flower visitors were attracted not only to the field border, but they were also present in the entire field. Our study confirms that increasing diversity of pollinator-dependent plants within-field and on the border of fields increases floral resources for pollinators and biological control agents, which both support agricultural production (Vialatte et al., 2017).

Most earlier studies on alternative practices to support pollinator and natural enemy diversity (Albrecht et al., 2020; Azpiazu et al., 2020; Ricketts et al., 2008) studied only distance to habitat and failed to examine the location within the field. Several studies showed a gradient of plant diversity from the edge to the center of the crop, associated with the same gradient of pollinator abundance. A study by Alignier et al. (2020) demonstrated that field borders have high plant diversity and flower richness due to the installation of wild flowers along the edges but not in the entire field. In our study, this is not the case as MHEP were installed every 15 m within the crop. This likely facilitates the movement of insects from the field edges towards the center. Poggio et al. (2013) found differences in floral diversity within fields due to variations in farming practices. Specifically, they observed that fields with lower intensity of herbicide application near the borders had higher floral diversity. Marshall and Moonen (2002) also noted the importance of farming practices in shaping floral diversity, particularly near field borders.

4.3. *Landscape effect on results in both regions*

This study emphasized the significance of regional effects, which can be correlated to altitude and land use (Hamdouni et al., 2018; Lahmar et al., 2020). Additionally, our findings revealed notable disparities in income levels and the abundance of flower visitors and natural enemies between regions. Sidi Slimane had less than 1/4 of the flower visitors compared to Ksar El-Kebir, with syrphids accounting for half of the flower visitors in Sidi Slimane.

Concerning syrphids, only two genera (Sphaerophoria and Syritta) were collected during the trial in the Sidi Slimane region, whereas in the Ksar El-Kebir region, seven genera (Eristalinus, Eristalis, Eupoedes, Ischiodon, Paragus, Sphaerophoria and Syritta) were collected. One reason for the high abundance of syrphids in the Sidi Slimane trials might be the higher abundance of Aphis gossypii, a melon pest and virus vector (Schoeny et al., 2019) that is preyed on by Syrphidae larvae. To

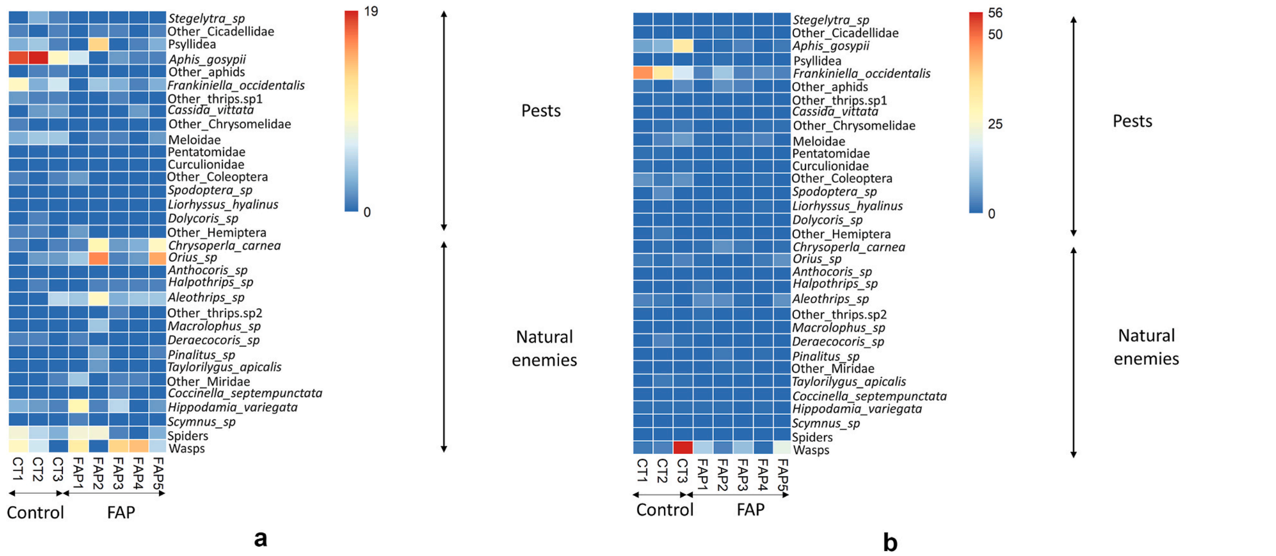

Fig. 3. Heatmap showing the abundance scores of natural enemies and pests in FAP and control fields for different sites in Sidi Slimane (Fig. 3a) and in Ksar El-Kebir (Fig. 3b). Darker red represents high abundance.

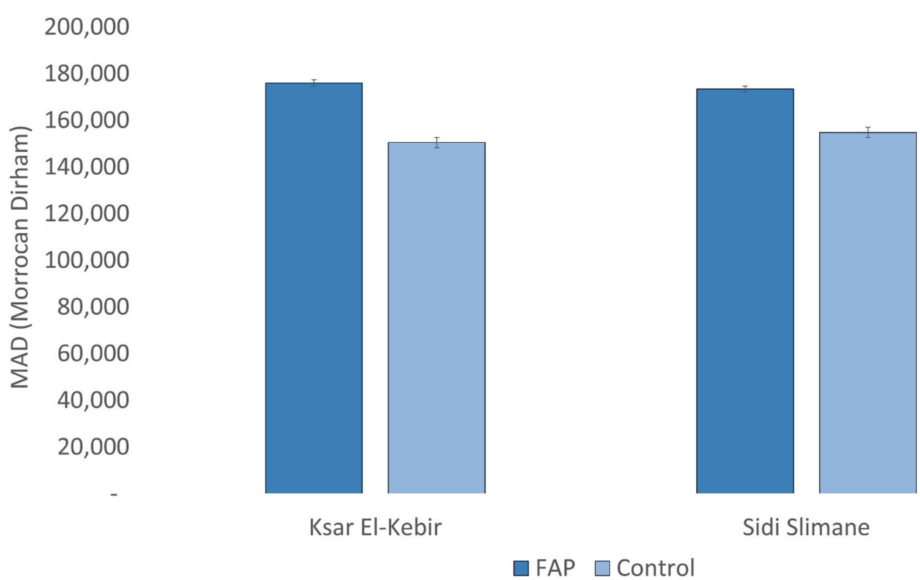

Fig. 4. Average net income from entire fields (1 ha) with melon as main crop in Ksar El-Kebir and Sidi Slimane.

explain the difference in hoverfly abundance between regions, a regional species pool is required, which, however, goes beyond the scope of this study. The different landscapes and climate conditions could have an effect on pest populations and syrphid communities. According to Subedi et al. (2023), syrphid flies have potential as pollinators and biological control agents. Aphidophagous syrphids frequently make regional dismigrations (undirected migrations) to find their prey and tend to build up high abundances if aphid densities are high (Haenke et al., 2014; Sutherland et al., 2001). Bee diversity was described in different regions in Morocco (Lhomme et al., 2020), but the current study regions were not included. Regarding wild bees, we found a considerable difference between abundance and diversity in Ksar El-Kebir fields and in Sidi Slimane fields. In our trial, the number of bee species of Sidi Slimane was low, possibly due to the intensity of agricultural practices in this region, known for the production of oranges which require a lot of pesticides (Darwesh et al., 2020).

Our results revealed an abundance of some natural enemies, such as Orius sp and wasps, in the main crop in FAP fields. Specifically, Aphis gossypii, was abundant only in control fields as this pest is considered a major pest of cucurbits and causes serious damage (Mistral et al., 2021). These results are in line with those of Schoeny et al. (2019) who observed that diversity of flower margins specifically designed for melon crops attracted significantly more aphid predators than monocultures. In Sidi Slimane, the landscape could negatively affect the abundance of beneficial insects as this region it known for its extensive fruit production, since landscape effects are more limited where plant richness is already high (Alignier et al., 2020). Marshall et al. (2006) highlighted the influence of landscape factors and field size on insect populations, i. e. abundances were enhanced by strips sown in small-scale landscapes.

Overall, we found a difference in income between the two regions, whereby income in Sidi Slimane was consistently lower compared to Ksar El-Kebir. This confirms that while abundance and diversity of bees can be positively correlated to farmers' incomes, this difference can also be due to climate difference, soil type and land use change between the regions (Garibaldi et al., 2014). More regions need to be sampled to identify the main factors.

5. Conclusion

While farmers are interested in higher yields and profits, adoption of new or alternative practices is challenging (Kleijn et al., 2019). Many farmers reject the concept of sowing wildflowers, due to fear of potential weed proliferation in their fields. These concerns are driven in part by the fact that many farmers are primarily focused on generating income from their crops (Christmann et al. 2017, 2021a, 2021b) and may be reluctant to adopt new practices that could increase their costs or reduce their incomes. Our study confirms that the FAP approach increases abundance and richness of flower visitors and natural enemies as well as the yield. This research shows how, in large Moroccan fields (1 ha), low-cost habitat enhancement by seeding MHEP within a pollinator-dependent main crop can enhance farmers' yields and incomes and provide broader benefits in agriculture that provide resiliency in the face of climate change, such as the conservation of insect fauna.

CRediT authorship contribution statement

Youssef Bencharki: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Denis Michez:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. **Oumayma Ihsane:** Formal analysis, Writing – review & editing. **Sara Reverté:** Writing – review & editing. **Aden Aw-Hassan:** Investigation, Writing – review & editing. **Moulay Chrif Smaili:** Investigation, Writing – review & editing. **Axel Ssymank:** Investigation, Writing – review & editing. **Pierre Rasmont:** Data curation, Resources, Supervision, Writing – review & editing. **Stefanie Christmann:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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